SUPERCONDUCTIVE DIGITAL INSTANTANEOUS FREQUENCY-MEASUREMENT SUBSYSTEM*

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[ABSTRACT]

A five-bit high-temperature-superconductive digital instantaneous frequency-measurement (DIFM) subsystem has been constructed for the determination of the frequency of unknown signals over a 500-MHz bandwidth, centered on 4 GHz, with a resolution of ± 7.8 MHz. The subsystem contains a cryogenic section with five discriminator modules utilizing superconductive delay lines, GaAs mixers, and power dividers. The subsystem also has a room-temperature GaAs limiting amplifier and a silicon postprocessor. With a single-tone CW input between -40 dBm and +10 dBm, the frequency quantization boundaries of the subsystem are, on average, 3.1 MHz from their design values.

I. Introduction

Instantaneous frequency-measurement (IFM) subsystems are used to determine the frequency of unknown signals over a broad frequency band [1]. Conventional IFM systems use delay lines made by coiling coaxial cables or (for shorter delay) by patterning meander lines of normal-metal microstrip. However, the loss and bulk of these techniques limits the amount of available delay. In order to recover sufficient frequency resolution with short delay lines, system designers are forced to use more accurate phase-detection schemes, placing demands on the mixers, phase shifters, and baseband circuitry used in the phase detectors [2]. In the present system, we exploit the compact nature of superconductive delay lines, each of which is part of a correlator performing a binary phase comparison. Superconductive delay lines offer the highest bandwidth with lowest loss and dispersion of any available technology. This makes it possible for us to use long delay lines and to make a simple binary phase detection scheme.

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II. Architecture of IFM Subsystem

The architecture of the present DIFM subsystem is shown in Figure 1. The incoming RF signal is split by a 5-way power divider to feed five phase-discrimination channels, each of which provides one bit of the frequency word. In each channel, the power is further split into two paths. One of these is applied directly to the correlation mixer LO port while the other is routed through a delay line, the output of which is fed to the mixer RF port. The phase correlation is obtained by lowpass filtering the output of the mixer. This baseband output is then hard limited to obtain the appropriate bit of the binary representation of the input signal frequency.

The delay in successive channels of the DIFM is stepped by a factor of two, with the exception of the two most significant bits (MSBs), which are the same length but with a 90-degree phase difference. This configuration produces a Gray code, which is then converted to natural binary code, and then to decimal form. The resolution of the system is +/- $(8\tau_{max})^{-1}$ where τ_{max} is the length of the longest delay line. In the subsystem, the longest line is 16 ns, giving a resolution of ± 7.8 MHz. (Resolution may be further enhanced by performing multi-bit phase measurement on the output of the discriminator with the longest delay.)

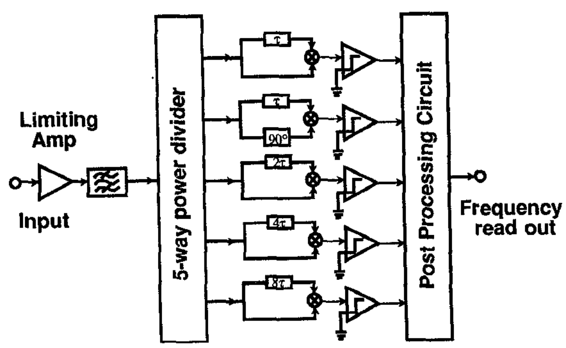

Fig. 1 Schematic diagram of the DIFM subsystem.

III. Implementation of the DIFM

This system utilizes HTS material extensively. The delay lines are made from $YBa_2Cu_3O_{7-\delta}$ (YBCO) films on 20-mil-thick $LaAlO_3$ substrates in a stripline configuration. The other components are made from silver and/or gold on M-plane sapphire substrates in a microstrip configuration. Key components are discussed further below.

Limiting amplifier: The limiting amplifier, with a bandpass filter, is used to increase the sensitivity and clean up the signal within the band of interest. The small-signal suppression effect of the limiter is also advantageous in reducing errors due to simultaneous input signals. We are using a five-stage GaAs FET amplifier which has an input power range from -40 dBm to +10 dBm and an output power of 16 dBm. With the output filter, this amplifier has a 35-dB suppression of adjacent harmonics.

Delay lines: The bandwidth, resolution, accuracy, and sensitivity of the DIFM is largely determined by the length and the quality of the delay lines. This system employs five delay lines with lengths of 16 ns, 8 ns, 4 ns, 2 ns, and 2 ns, respectively. All are made on 20-mil-thick $LaAlO_3$ substrates in a stripline configuration, with 100-μm linewidth (with 40-Ω characteristic impedance) and tapered line transformers to 50-Ω impedance at both ends [3, 4]. The gold-plated aluminum package of the delay line employs a bed of beryllium-copper (BeCu) springs to press against the thin dielectric substrates and keep them in intimate contact with each other [5].

Cryogenic mixers: Single-balanced mixers with GaAs Schottky diodes are used in phase discriminators. By operating the mixers within the cryogenic enclosure, only one IF cable (with low thermal conductance) per discriminator is required, while two microwave cables (with high thermal leakage) would be necessary if the mixers were at room temperature. In order to reduce the required power level, we use low-barrier-height diodes which have a barrier height of 0.2 V. The LO signal is applied to a microstrip launcher and the RF signal is coupled to the diodes by two sections of quarter-wave balun.

Power dividers: We utilize a standard Wilkinson power divider for the two-way power splitting. For the five-way splitting, we have modified the conventional power divider by combining radial and planar configurations. Figure 2 is the layout of the five-way power divider. We added resistors R_a and R_b for more symmetry, increasing the bandwidth and enhancing the isolation. Computer simulation predicts that the return loss of both the input and output are more than 20 dB, and the isolation is over 20 dB. The output power split is designed to be unequal to compensate for the insertion-loss difference in the different delay lines. The design output powers in this splitter are -6.5 dB (port 3), -7.0 dB (ports 2 & 4), and -9.5 dB (ports 1 & 5).

One of the 2-ns channels requires a quadrature phase shifter. We use a four-finger Lange coupler to accomplish this 90° phase shift as well as the power division.

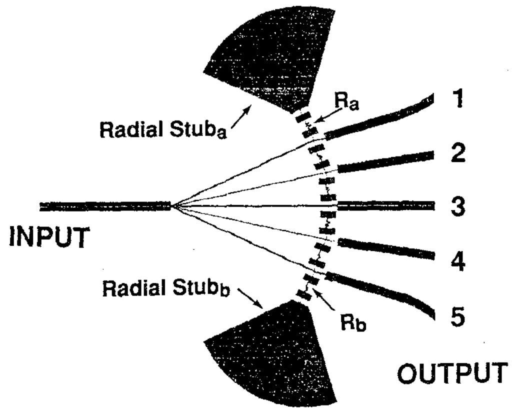

Fig. 2 Layout of the five-way power divider.

Package: The overall package consists of six subpackages. Five of these are discriminator modules containing mixers and delay lines, which are a combination of stripline and microstrip line configurations. The sixth subpackage contains the five-way power divider in a microstrip configuration. These six subpackages are electrically connected by five "snap on" SMA connectors. Figure 3 is a photograph of the assembled cryogenic section. Figure 4 shows a 16-ns discriminator module.

Room-temperature postprocessor: The postprocessor has a fast differential comparator which can operate above 30 MHz. The comparator output is designed to be 5-bit Gray code, representing the instantaneous frequency of the input signal. The Gray code is converted to binary code and then to decimal and is displayed.

IV. Experimental Results and Discussion

We have fabricated and tested each part of the subsystem and evaluated the overall system performance. The performance of the components, modules, and complete IFM system is described below:

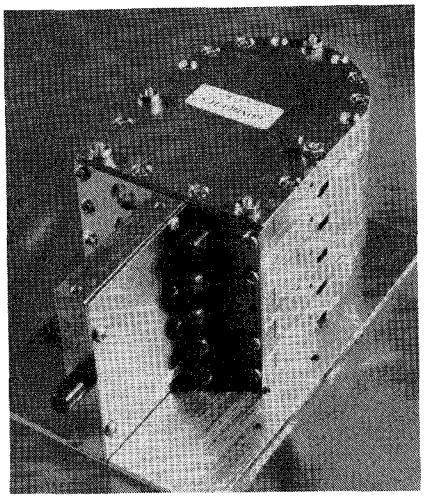

Fig. 3 Cryogenic section of DIFM system. The vertical section (bottom left) is the 5-way power divider. The five discriminator modules (top right) are stacked.

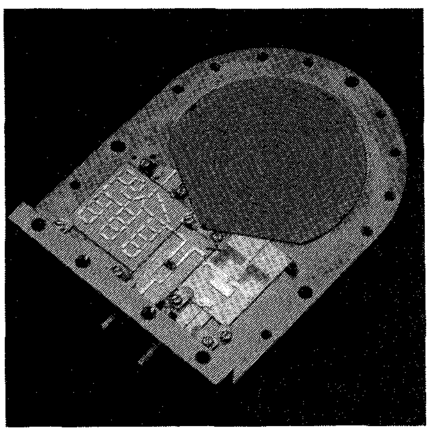

Fig. 4 Discriminator module with 16-ns delay line. The components are: bottom left - trimming delay line; bottom middle - a two-way power divider; bottom right - a self-biased mixer; upper right - a spiral delay line on $LaAlO_3$ substrate, with upper ground plane of the stripline removed to reveal the pattern.

a) Delay lines: In the current DIFM system we have used 2, 2, 4, 8, and 16 ns delay lines on 20-mil-thick $LaAlO_3$ substrates. Scattering parameters of these delay lines have not been measured outside of the discriminator modules. However, a comparable delay line, a 15.2-ns delay line on $LaAlO_3$ made at Conductus, has less than 3-dB insertion loss at 77 K at 6 GHz .

b) Mixers: The conversion loss at 4 GHz was measured to be 7 dB at 77 K and 10 dB at 300 K. The variation is +/- 0.75 dB within the 500-MHz bandwidth.

c) Power dividers: The measured return loss for the two-way power divider is 15 dB. The insertion loss to both output ports is 3.1 +/- 0.1 dB across the band. The five-way power divider shows a 16-dB return loss on the input port, 23- to 28-dB return loss on the outputs, and a 20 to 25-dB isolation between the outputs. The output power split at 300 K is -7.1 dB (port 3), -8.5 dB (ports 2 & 4), and -9.3 dB (ports 1 & 5).

d) One-bit discriminator module: A delay-trim network is used in conjunction with the delay line. Alternate paths through Au/sapphire microstrip trim circuit are selected by wire bonding so that the zero crossings of discriminator IF outputs occur at the correct frequencies. The delay can be trimmed in units of 36 ps, and fine trimming can be made to 10 ps. Each comparator threshold value is also independently adjusted.

e) Complete system test : The complete system has been tested in liquid nitrogen. Figure 5 shows the digital output of the room-temperature postprocessor unit, with a single swept input tone, as a function of the input frequency. The outputs of the 2-ns (in phase), 2-ns (quadrature), 4-ns, 8-ns, and 16-ns channels are arranged from top to bottom. Figure 6 shows the frequency reported by the DIFM, under CW condition with a single stepped input tone, where the x-axis is the input frequency and the y-axis is the readout frequency indicated by the decoded binary signals shown in Fig. 5. Figure 7 shows the deviation of the transition frequencies (that is, the frequencies at which the binary output changes) from the design values. The average of the magnitude of the error is 3.1 MHz. The input power dynamic range is between -40 dBm and +10 dBm.

We have also performed a dual-tone test without the limiting amplifier using two CW sources within the DIFM band. One source, with a constant power of 11.7 dBm, is sweeping over the band, while the other, weaker tone is tuned to 3.8 GHz. The DIFM accurately reports the frequency of the stronger signal as long as the second signal is 10 dB lower. By using the limiting amplifier, with its small-signal suppression effect, the tolerable power difference can be 6 dB smaller.

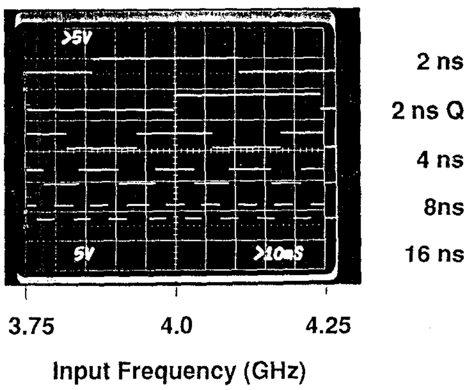

Fig. 5 The 5-bit digital output of the DIFM as a function of input frequency.

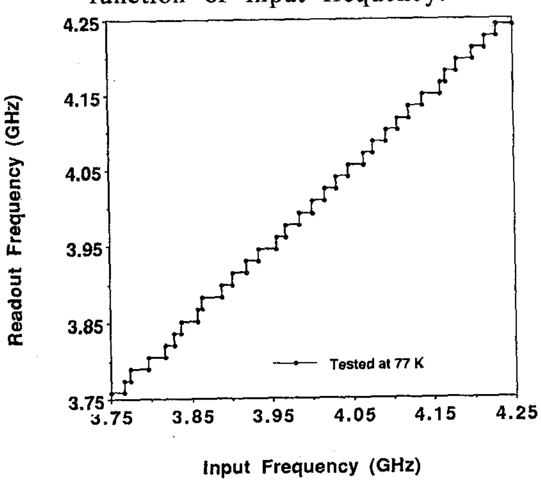

Fig. 6 DIFM frequency readout versus input frequency (CW test).

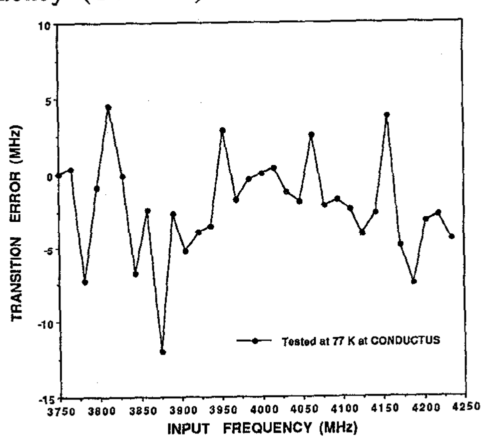

Fig. 7 Deviation of transition frequencies from the design values.

V. Conclusion

We have reported a five-bit superconductive digital instantaneous frequency measurement (DIFM) subsystem. The system has a center frequency of 4 GHz and a bandwidth of 500 MHz. The subsystem contains a cryogenic section with five discriminator modules utilizing superconductive delay lines, GaAs mixers, and power dividers. The subsystem also has a room-temperature GaAs limiting amplifier and a silicon postprocessor. With a single-tone CW input power between -40 dBm and +10 dBm, the frequency quantization boundaries of the subsystem are, on average, 3.1 MHz from their design values.

VI. Acknowledgment

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VII. References

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